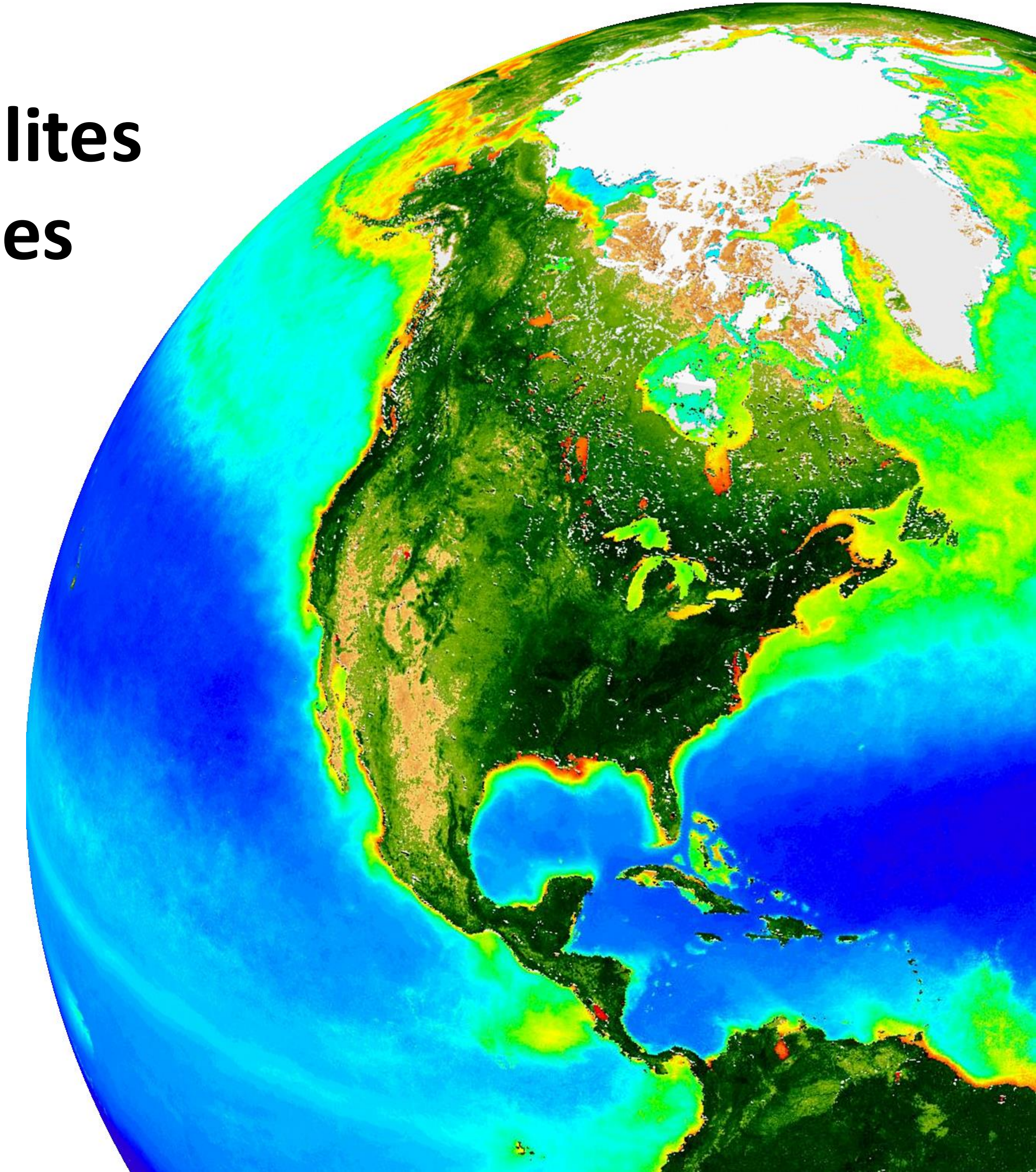
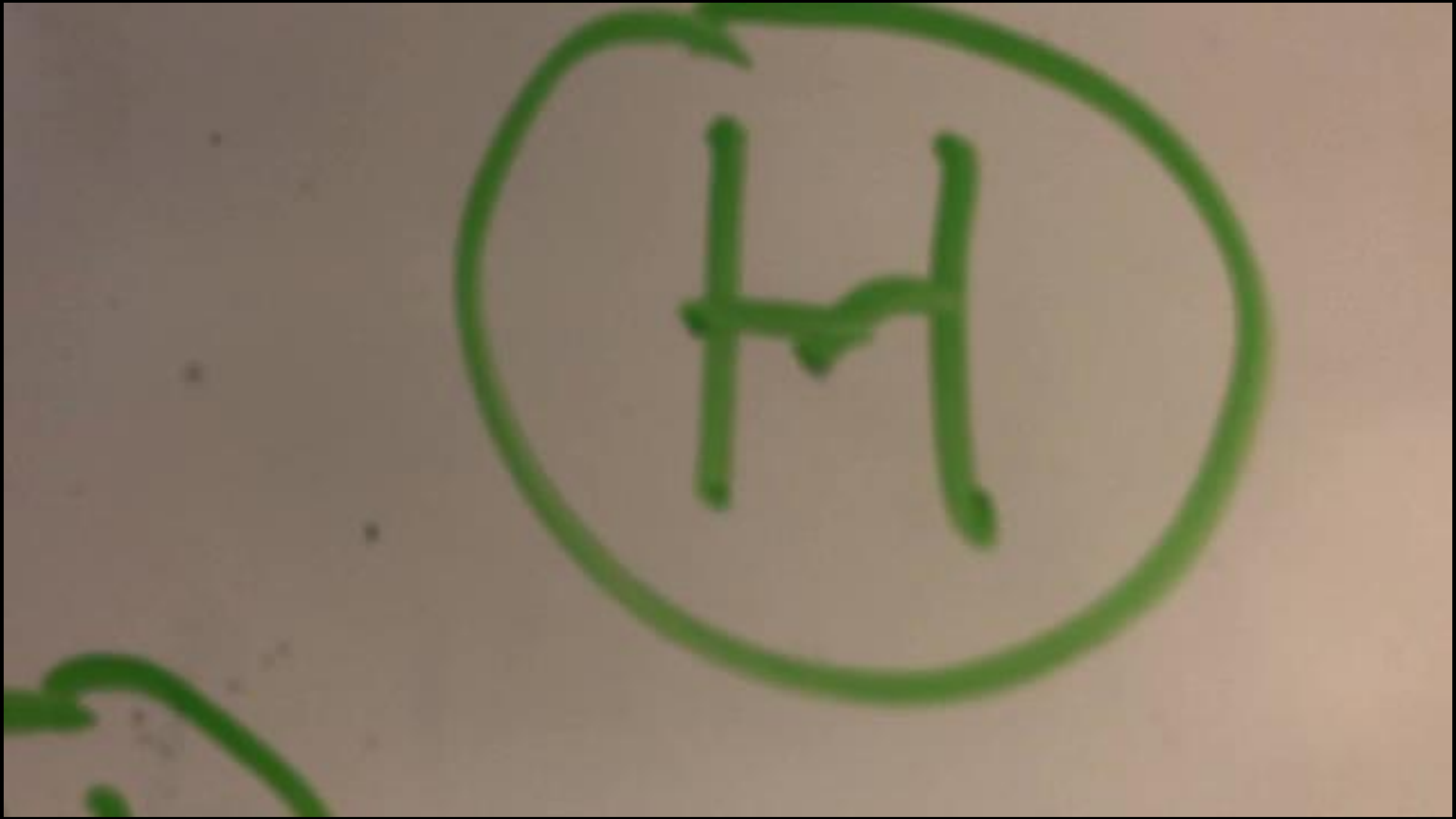
Why don’t all ocean color satellites measure hyperspectral radiances at meter-scales?

Jeremy Werdell
NASA Goddard Space Flight Center

Acknowledgements:
Gary Davis, Bryan Monosmith, Ryan Vandermuelen,
Ivona Cetinić & Curt Mobley

2025 Ocean Optics Summer Course

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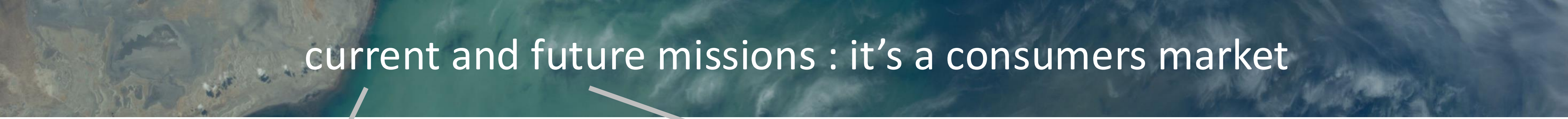


current and future missions : it's a consumers market

SENSOR / DATA LINK	AGENCY	SATELLITE	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	BANDS	SPECTRAL COVERAGE (NM)	SPECTRAL RESPONSE FUNCTION	EQUATORIAL CROSSING TIME
COCTS CZI	NSOAS/CAST (China)	HY-1D	11 June 2020	3000 950	1100 50	10 4	402 - 12,500 433 - 885		13:30
COCTS CZI	NSOAS/CAST (China)	HY-1C	7 September 2018	3000 950	1100 50	10 4	402 - 12,500 433 - 885		10:30
GOCI-II Geostationary	KARI/KIOST (South Korea)	GeoKompsat-2B	18 February 2020	2500 x 2500	250	13	380 - 900	SRF-link	10 times/day
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	4 May 2002	2330	250/500/1000	36	405-14,385	SRF-link	13:30
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	18 Dec 1999	2330	250/500/1000	36	405-14,385	SRF-link	10:30
MSI	ESA	Sentinel-2A	23 June 2015	290	10/20/60	13	442-2202	SRF-link	10:30
MSI	ESA	Sentinel-2B	7 March 2017	290	10/20/60	13	442-2186	SRF-link	10:30
OCM-2	ISRO (India)	Oceansat-2 (India)	23 Sept 2009	1420	360/4000	8	400 - 900		12:00
OLCI	ESA/ EUMETSAT	Sentinel 3A	16 Feb 2016	1270	300/1200	21	400 - 1020	SRF-link	10:00
OLCI	ESA/ EUMETSAT	Sentinel 3B	25 April 2018	1270	300/1200	21	400 - 1020	SRF-link	10:00
SGLI	JAXA (Japan)	GCOM-C	23 Dec 2017	1150 - 1400	250/1000	19	375 - 12,500	SRF-link	10:30
VIIRS	NOAA (USA)	Suomi NPP	28 Oct 2011	3000	375 / 750	22	402 - 11,800	SRF-link	13:30
VIIRS	NOAA/NASA (USA)	JPSS-1/NOAA-20	18 Nov 2017	3000	370 / 740	22	402 - 11,800	SRF-link	13:30

SATELLITE	AGENCY	SENSOR / DATA LINK	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	# OF BANDS	SPECTRAL COVERAGE (NM)	ORBIT
HY-1E/F (China)	CNSA (China)	CZI	2021	2900 1000	1100 250	10 4	402 - 12,500 433 - 885	Polar
EnMAP	DLR (Germany)	HSI	2021-2022	30	30	242	420 - 2450	Polar
OCEANSAT-3	ISRO (India)	OCM-3	end-2021	1400	360 / 1	13	400 - 1,010	Polar
SABIA-MAR	CONAE	Multi-spectral Optical Camera	2023	200/2200	200/1100	16	380 - 11,800	Polar
PACE	NASA	OCI SPEXone HARP-2	2023	2000 100 1550	1000 2500 3000	Hyperspec (5 nm, 350-890nm + 7 bands NIR-SWIR) Hyperspec (2 nm) 4 bands	350-2250 nm 385-770 nm 440-870 nm	Polar
GISAT-1	ISRO (India)	MX-VNIR HyS-VNIR HyS-SWIR	12 August 2021	470 160 190	42 320 191	6 158 256	450-875 375-1000 900-2500	Geostationary (35.786 km) at 93.5°E
SBG	NASA	*Hyper-VSWIR *TIR-Imager	2026	~185 ~600	30 60-100	>200 ~8	380-2500	Polar
GLIMR	NASA	*VNIR-imager *WFOV-sensor	>2023	TBD	300 133	141	340-1040	Geostationary -Cont.US coasts, Amazon, Caribbean

IOCCG International Ocean Colour Coordinating Group

why include this talk?

My prediction is that >50% of you will someday:

1. **use satellite data for your research and wish to understand engineering design choices** (== shake your fist at the clouds and shout “*why are there so many options and differences across instruments?*”)

2. serve as members of space agency Science Definition Teams
   (or equivalent, e.g., 2017 Decadal Survey “designated observable” teams)

3. serve on satellite mission review boards or proposal panels

4. write proposals for new missions (or field campaigns or instruments)

5. build something that requires trade space and a fixed budget

chasing photons – considerations for making & maintaining useful satellite ocean color measurements

Contents

alternative title: the trade space within which you will work when creating an instrument design concept

why don't all ocean color satellites measure hyperspectral radiances at meter-scales?

3 case studies:

(1) stationary satellite staring at 1 m^2 for 1 s
(2) moving satellite staring at 1 m^2
(3) moving satellite scanning side to side

$$SNR = \frac{N_{electrons}}{\sqrt{N_{electrons}}}$$

(oversimplification; assumes no dark current or noise)

what we will (hopefully) learn:

- how many photons leave a 1 m^2 of ocean surface
- how many photons from this patch reach the satellite detector
- how many photons must the detector collect to achieve useful SNR

consider a satellite instrument with the following characteristics

these numbers are just for reference for the exercise – don't stare too hard

optical efficiency (OE) = 0.6
quantum efficiency (QE) = 0.9
aperture = 0.09 m (90 mm)
view angle = 20 deg
altitude = 705,000 m (705 km)
slant range = 750,000 m (750 km)

solid angle of aperture (sensor) as seen from earth's surface = 4.5 e^{-14} sr

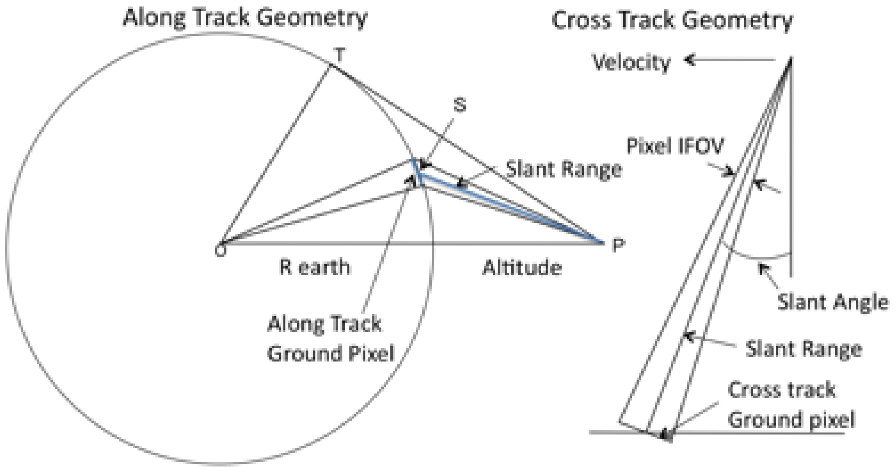
ground velocity = 6838 m s^{-1}

parts observatory

let's focus on a fluorescence channel:

wavelength = 0.678 μm (678 nm)
bandwidth ($\Delta\lambda$) = 0.010 μm (10 nm)
typical TOA radiance = 14.5 W m^{-2} μm^{-1} sr^{-1}
desired SNR = 2000

satellite viewing geometry



case 1 : a stationary satellite taking a quick peek at Earth

power reaching detector for 1 m^2 areal footprint & 1 s integration time:

$P_{detector}$	=	L	$\Omega_{aperture}$	$Area_{surface}$	OE	$\Delta\lambda$
3.94e^{-15}	=	14.5	4.5e^{-14}	1	0.6	0.01
W	=	W m^{-2} sr^{-1} μm^{-1}	sr	m^2	(none)	μm

photoelectrons reaching detector:

$N_{electrons}$	=	$P_{detector}$	t	QE	λ	h^{-1}	c^{-1}
12074	=	3.94e^{-15}	1	0.9	0.678	(6.63e^{-34})$^{-1}$	(3e^{14})$^{-1}$
(none)	=	J s^{-1}	s	(none)	μm	J^{-1} s^{-1}	s μm^{-1}

integration time needs to be raised to 6 minutes to get SNR of ~ 2100

this is for top-of-atmosphere → SNR =~ 109

if we consider that the ocean contributes ~5% of this signal, then the **number of photoelectrons from the ocean surface reaching the detector is ~603**

case 2 : a moving satellite that stares at 1 m^2 at nadir

ground velocity = distance / time
6838 m s^{-1} = 1 m / t
integration time = 0.000146 s

repeat calculations with new integration time …

… photoelectrons from ocean surface reaching detector ~ 0.088 → SN 33

but, increase pixel size to 1 km^2 …

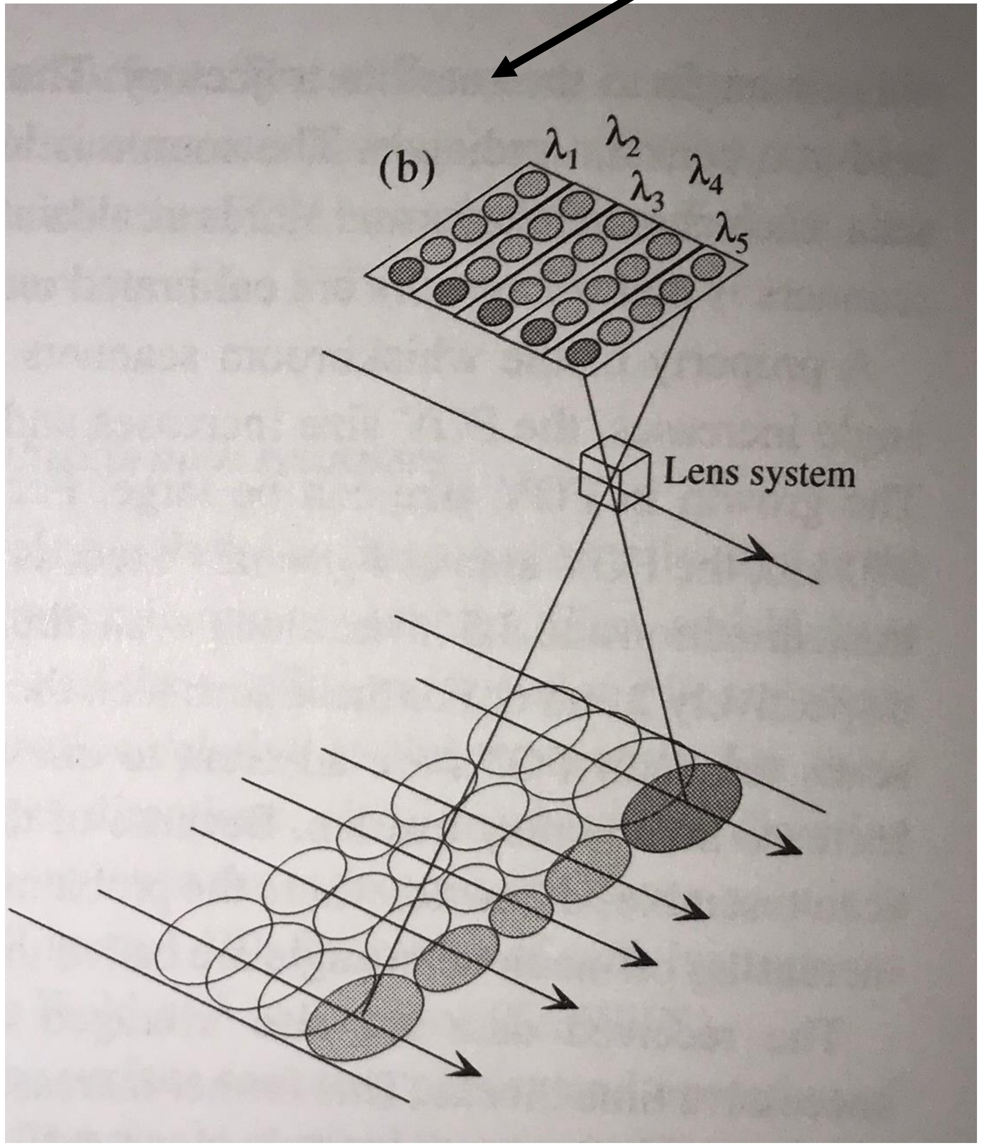
- integration time increases by 3 orders of magnitude
- area increases by 6 orders of magnitude

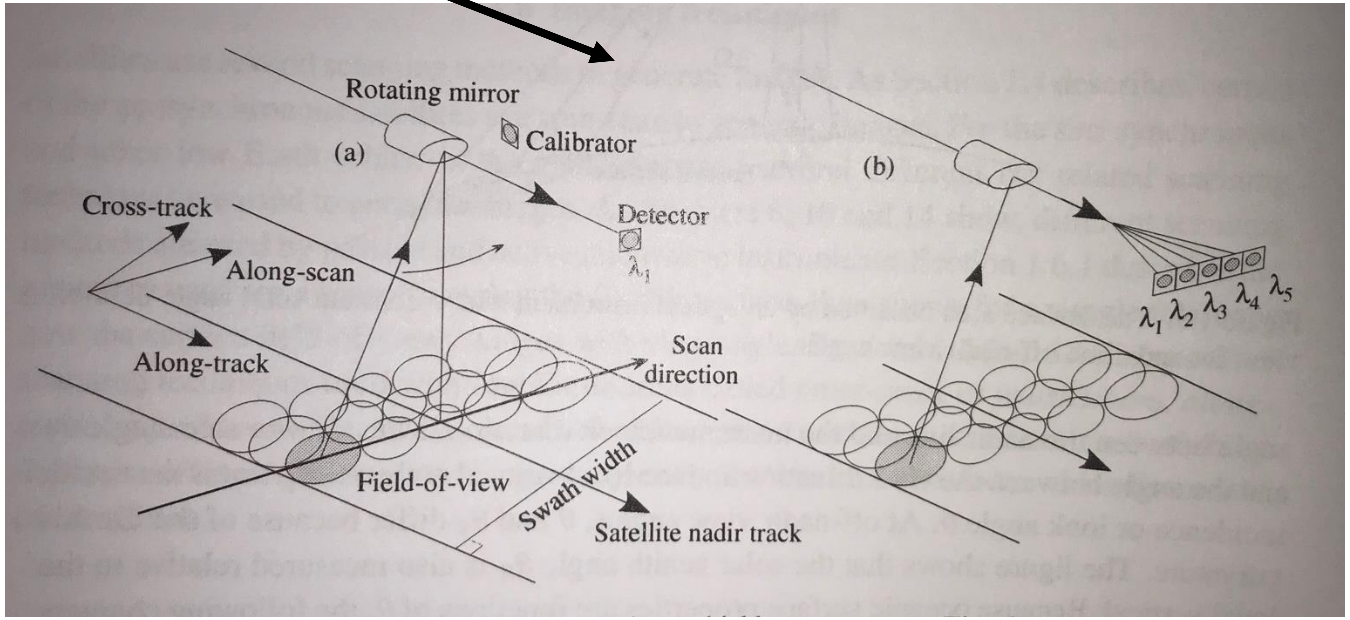
major reason why pushbroom instruments are attractive … SNR ~ 2400 for a 150 m pixel

repeat calculations with new area and integration time …

… photoelectrons from ocean surface reaching detector ~ 88,300,000 → SNR =~ 42021

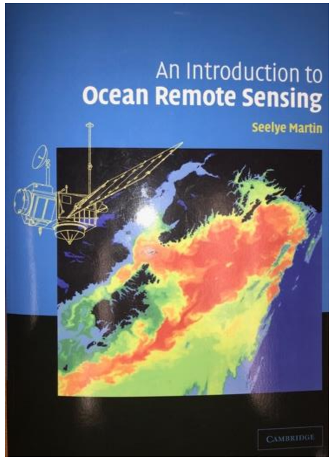
pushbroom vs. whiskbroom (scanner)





HICO
Landsat 8 OLI
MERIS
OLCI

SeaWiFS
MODIS
VIIRS
PACE OCI



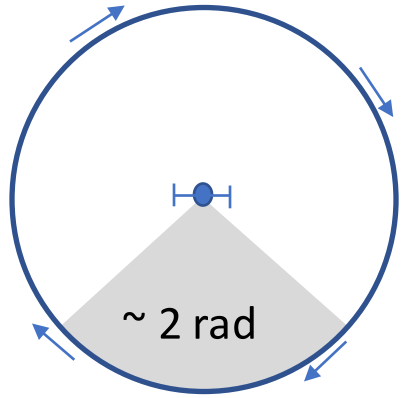
case 3 : consider a moving satellite that scans from side-to-side

wide-swath scanning instrument like SeaWiFS & PACE OCI

keep the 1 km pixel, but rotate the telescope at 1 Hz

instantaneous field of view (IFOV) ~ pixel size / altitude
0.00133 rad ~ 1 km / 750 km

a swath width of ~2 rad translates to ~1,500 pixels:
= swath width / IFOV
1,504 = 2 rad / 0.00133 rad

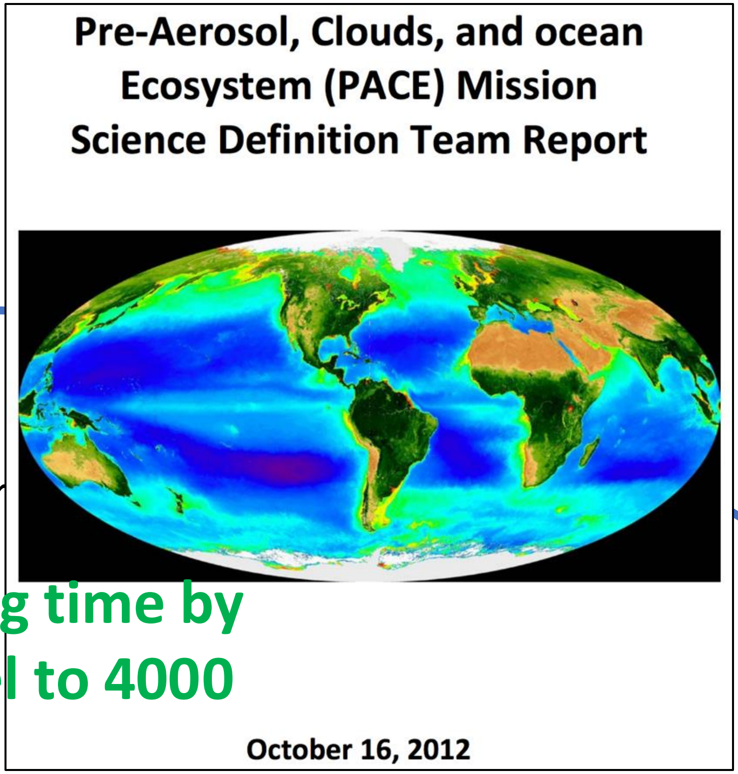


dividing the 88M photoelectrons by 1,500 pixels leaves **~59,000 photoelectrons from the ocean surface reaching the detector**

useful duty cycle of of scan mirror is < 1/3, **so really, we're talking about ~19,600 ocean surface photons**

propagating this to TOA results in ~392,000 photons reach detector → SNR =~ 626

case 3 : consider a moving satellite that scans from side-to-side


Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report

October 16, 2012

requires >10x photons reaching the detector

(… especially since most telescopes r

λ	Band Width (nm)	Spatial Resol. (km^2)	L_{typ}	L_{max}	SNR-Spec
350	15	1	7.46	35.6	300
360	15	1	7.22	37.6	1000
385	15	1	6.11	38.1	1000
412	15	1	7.86	60.2	1000
425	15	1	6.95	58.5	1000
443	15	1	7.02	66.4	1000
460	15	1	6.83	72.4	1000
475	15	1	6.19	72.2	1000
490	15	1	5.31	68.6	1000
510	15	1	4.58	66.3	1000
532	15	1	3.92	65.1	1000
555	15	1	3.39	64.3	1000
583	15	1	2.81	62.4	1000
617	15	1	2.19	58.2	1000
640	10	1	1.90	56.4	1000
655	15	1	1.67	53.5	1000
665	10	1	1.60	53.6	1000
678	10	4	1.45	51.9	2000
710	15	1	1.19	48.9	1000
748	10	1	0.93	44.7	600
820	15	1	0.59	39.3	600
865	40	1	0.45	33.3	600
1240	20	1	0.088	15.8	250
1640	40	1	0.029	8.2	180
2130	50	1	0.008	2.2	15

in this experiment, reducing time by 1/6 and increasing the pixel to 4000 km, gives an SNR of 2046

useful duty cycle of of scan mirror is < 1/3, **so really, we're talking about ~19,600 ocean surface photons**

propagating this to TOA results in ~392,000 photons reach detector → SNR =~ 626 satellite instruments come in all shapes and sizes and have varying capabilities

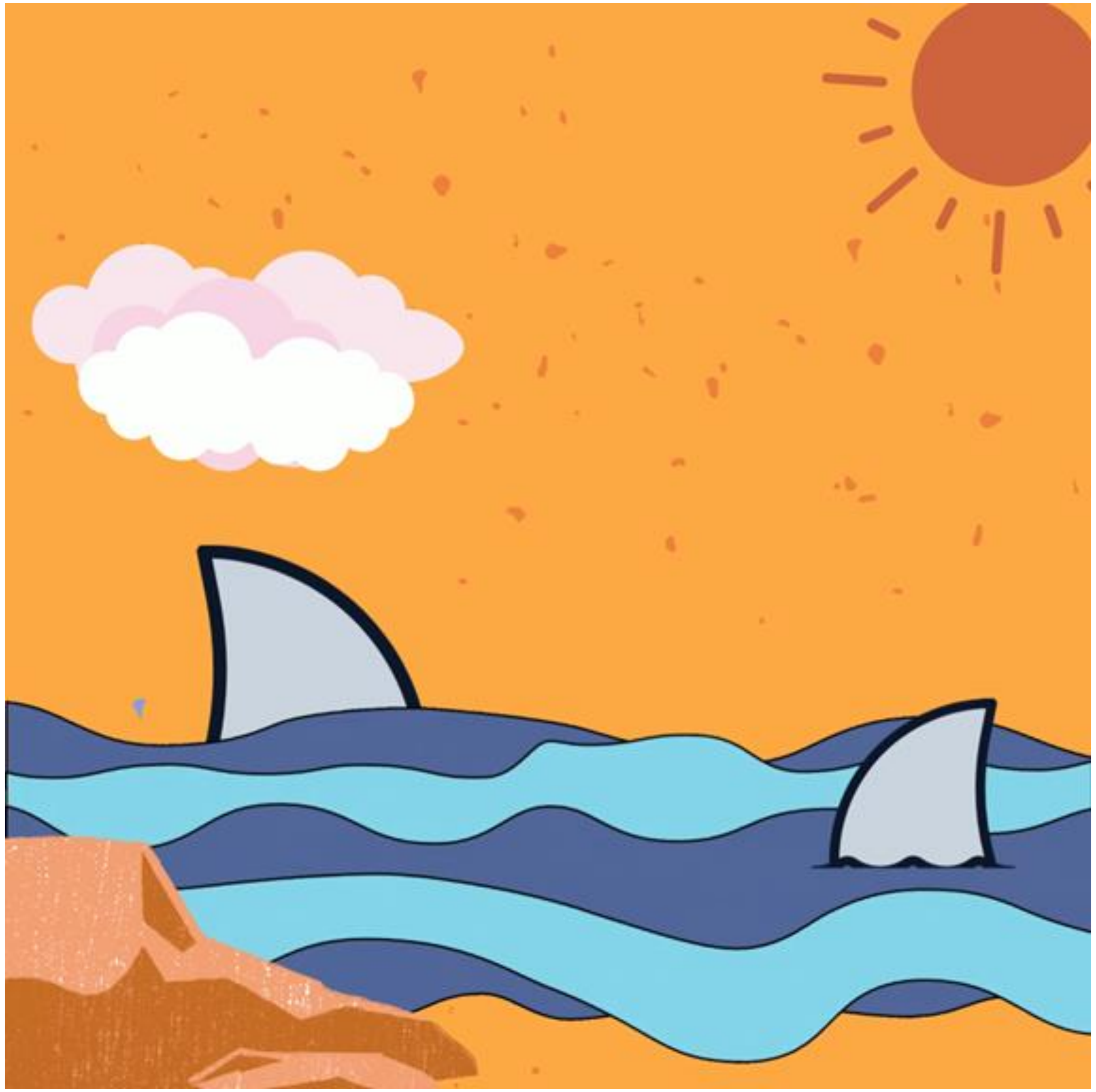
how does one choose what to use / build?

how would you design a mission to monitor coastal harmful algal blooms & their interactions with the atmosphere under pervasive absorbing aerosols?

Optics Class
Class
Shark Tank
exercise

(aka build a mission with your new co-PIs)

Jeremy (courtesy of Ivona and Ryan)



goal : build your own mission

1. Find your team members (maybe groups of 5?)
2. Think about the assigned science question (coastal HABs + abs aer)
3. Think what kind of space-based observation would you need to get data to address that question (you can copy already existing missions a bit)
4. Your budget its 100$ (and you are cost capped) – go shopping
5. Cool acronym (or yeah not a real mission)

What measurements & data products?

All of them.

What instruments? Active? Passive?

Both.

Spectral – what wavelengths? Thermal?

Yes please! UV-to-SWIR plus thermal.

Spectral – what resolution?

Hyperspectral, of course.

What spatial footprint?

The smaller the better. 10 m!

What repeatability?

Daily global, duh. Phytos are transient.

What allowable image quality?

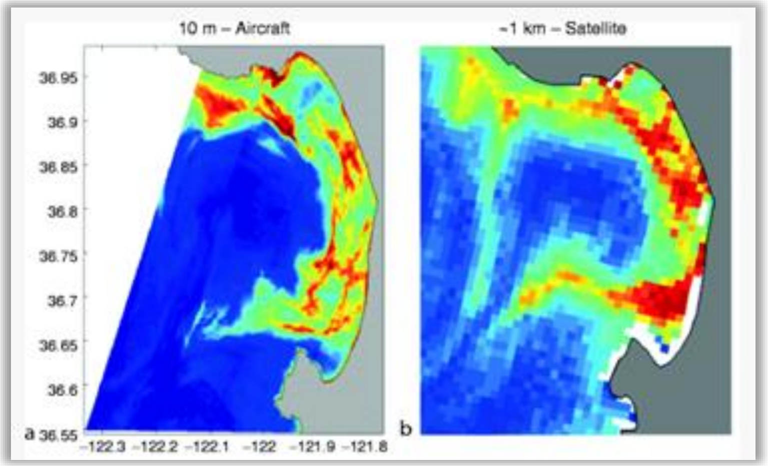
High SNRs, no image artifacts.

What temporal stability?

Change is bad.

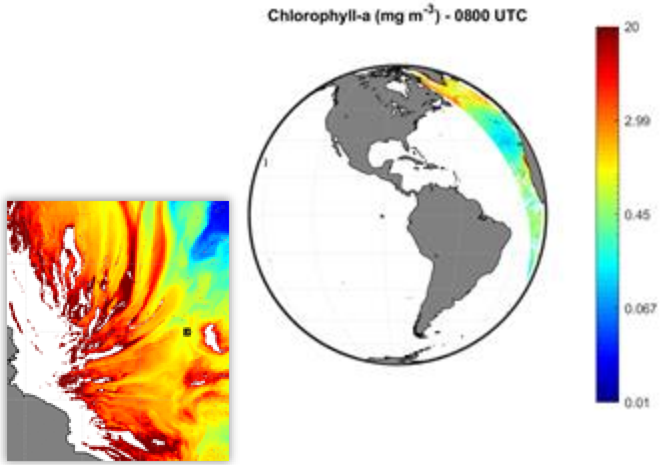
You can't have this mission
(from orbit alone anyway).

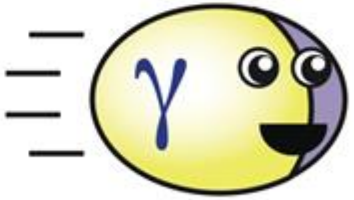
the battle over the happy photon

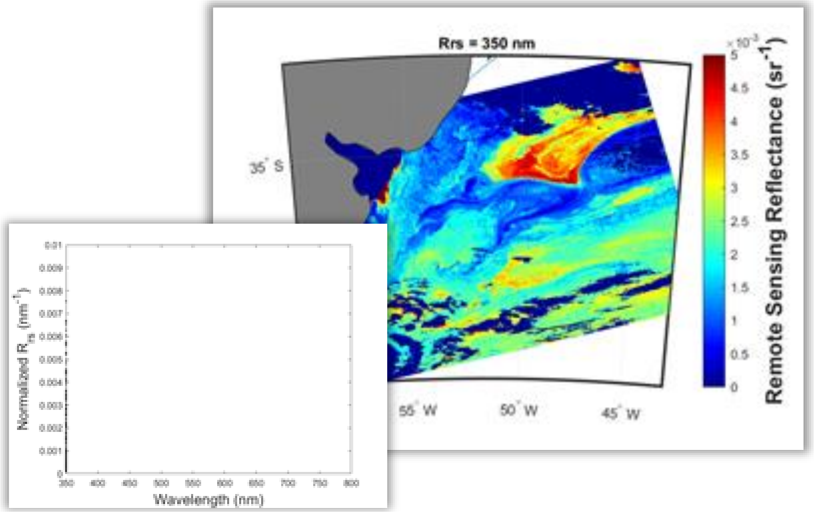


spatial resolution

temporal resolution

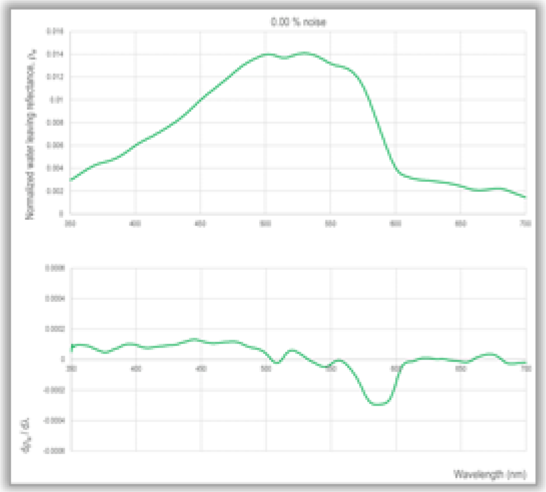




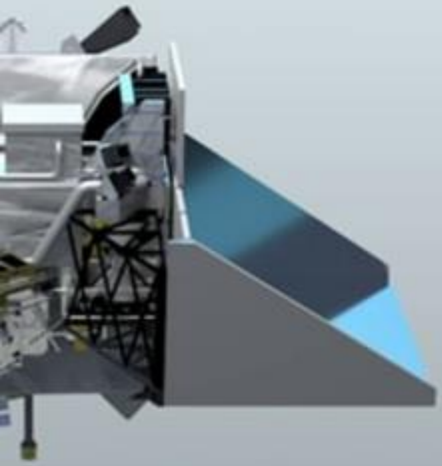


spectral resolution

signal to Noise



SATELLITE
Cafe



GRATUITY(AKA LAUNCH + SPACECRAFT) = 20%

OPEN :
MON-SUN
7 AM - 5 PM

123 Anywhere St., Any City, ST 12345

INSTRUMENTS (VIS)

multispectral (10) radiometer	$35
HYPERSPECTRAL radiometer	$55
multispectral (3) radiometer	$25
Hyperspec, multiangle polarimeter	$45
lidar, single channel	$50
instrument yet to be invented	$80
multispec (4), multiangle polarimeter	$40

SPATIAL RES

1 km (radiometer)	$25
300 m (radiometer)	$40
1 km (polarimeter)	$50
10 m (radiometer)	$65
2-3 km (radiometer)	$25

TEMPORAL RES

DAILY	$25
7-10 DAYS	$10
MULTIPLE TIMES A DAY (GEO)	$35
MULTIPLE TIMES A DAY (constellation)	$20

ADD ONS

SWIR	$10
UV	$10
THERMAL	$15
additional bands in vis	$2
additional angles	$4
more than occasional artifact	-$7
low SNR (lower than pace instr)	-$15
higher-than-planned SNR at spec. range	-$5
Calibration (MORE reliable): On board calibrator	$5
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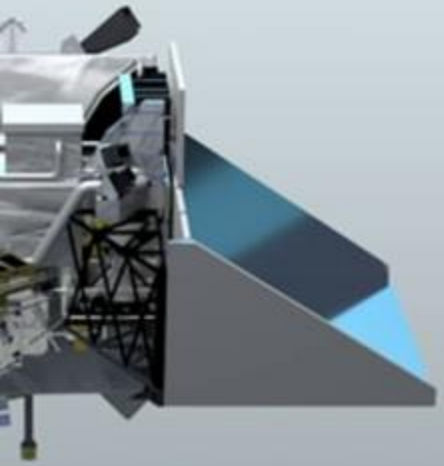

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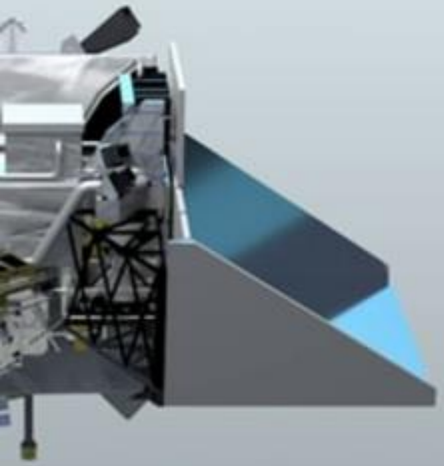

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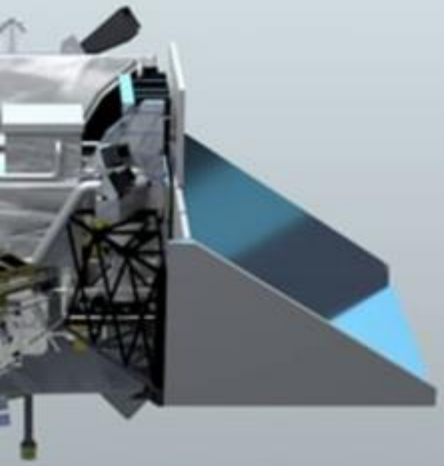

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what if you go over budget?

this includes schedule slips because **time does indeed equal money**

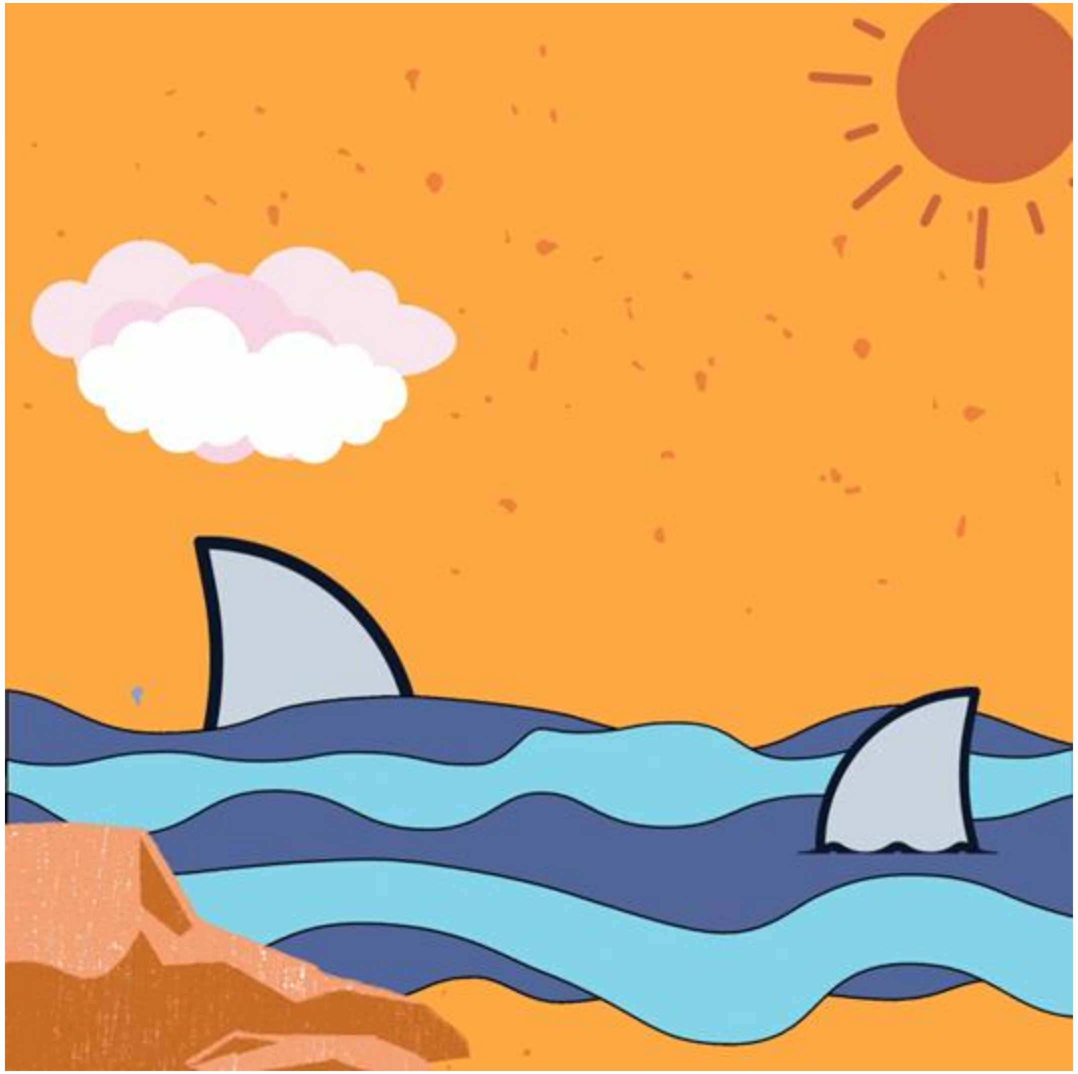
the review panel (who debriefs HQ) or HQ (alone) will decide your fate …

1. they give you money

2. they cancel you

3. you get put on a shelf

4. you get eaten by sharks



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What allowable image quality?

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What temporal stability?

Change is bad.

You can't have this mission
(from orbit alone anyway).

You have neither the budget …
… nor the technology.

And certain aspects of the design are in conflict with each other.

So … we make compromises based on overarching science objectives.


How to choose?
PACE
Plankton, Aerosol, Cloud, ocean Ecosystem

Extend key systematic **ocean** biological, ecological, & biogeochemical climate data records, as well as **cloud** & **aerosol climate data records**

Make **new global measurements of ocean color** that are essential for understanding the global carbon cycle & ocean ecosystem responses to a changing climate

Collect **global observations of aerosol & cloud properties**, focusing on reducing the largest uncertainties in climate & radiative forcing models of the Earth system

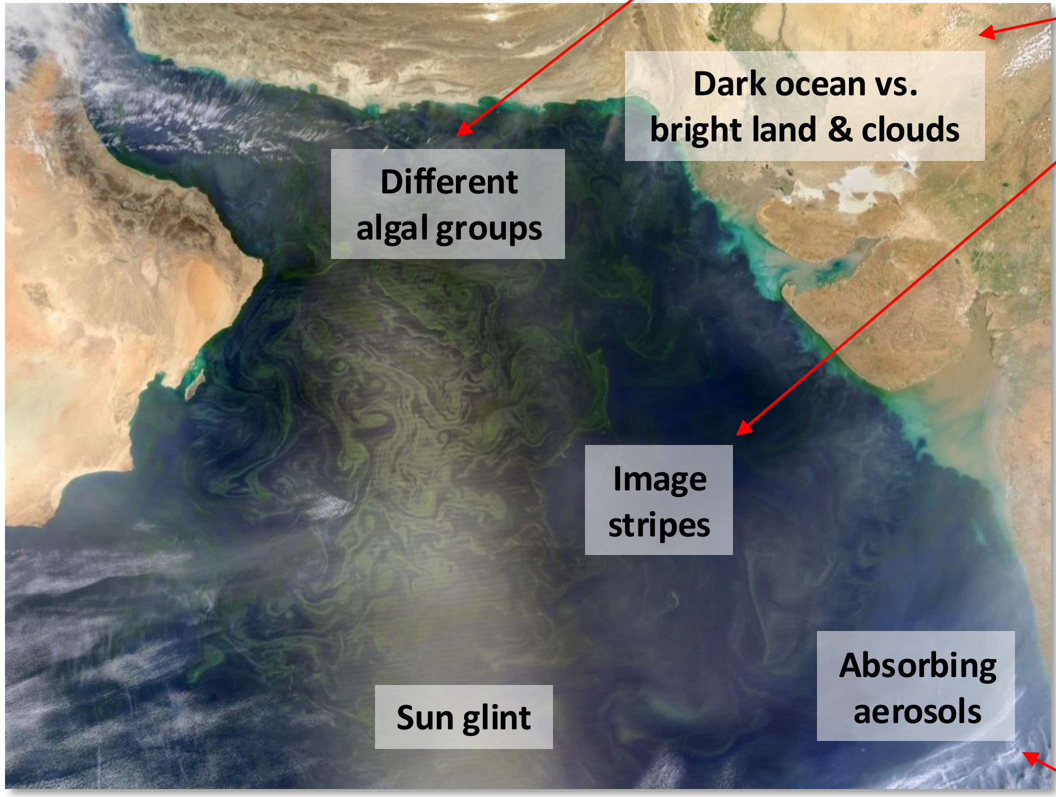
GSD of 1 ± 0.1 km² at nadir

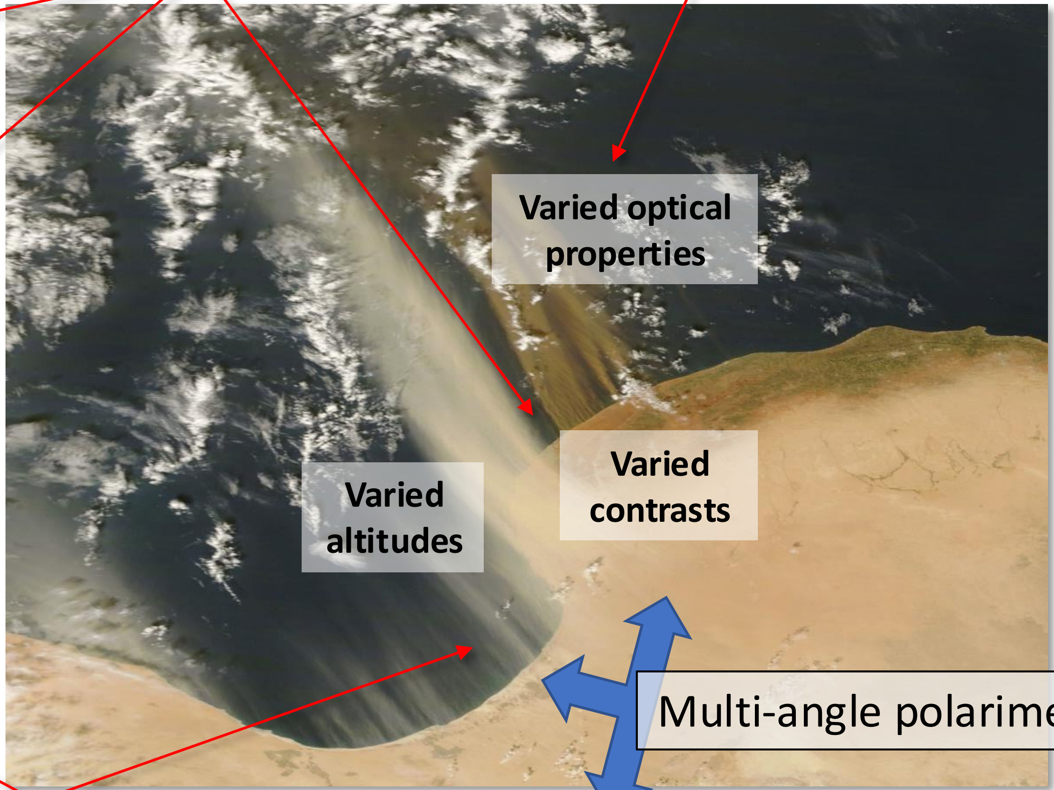
Twice-monthly lunar calibration & onboard solar calibration (daily, monthly, dim)

Spectral range from 350-865 @ 5 nm

940, 1038, 1250, 1378, 1615, 2130, 2260 nm

Instrument performance requirements

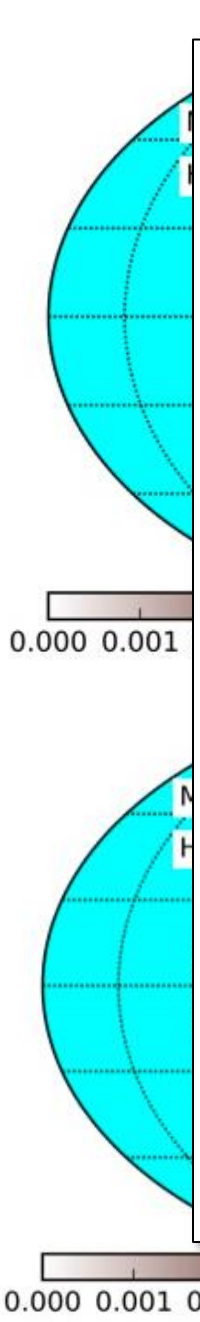


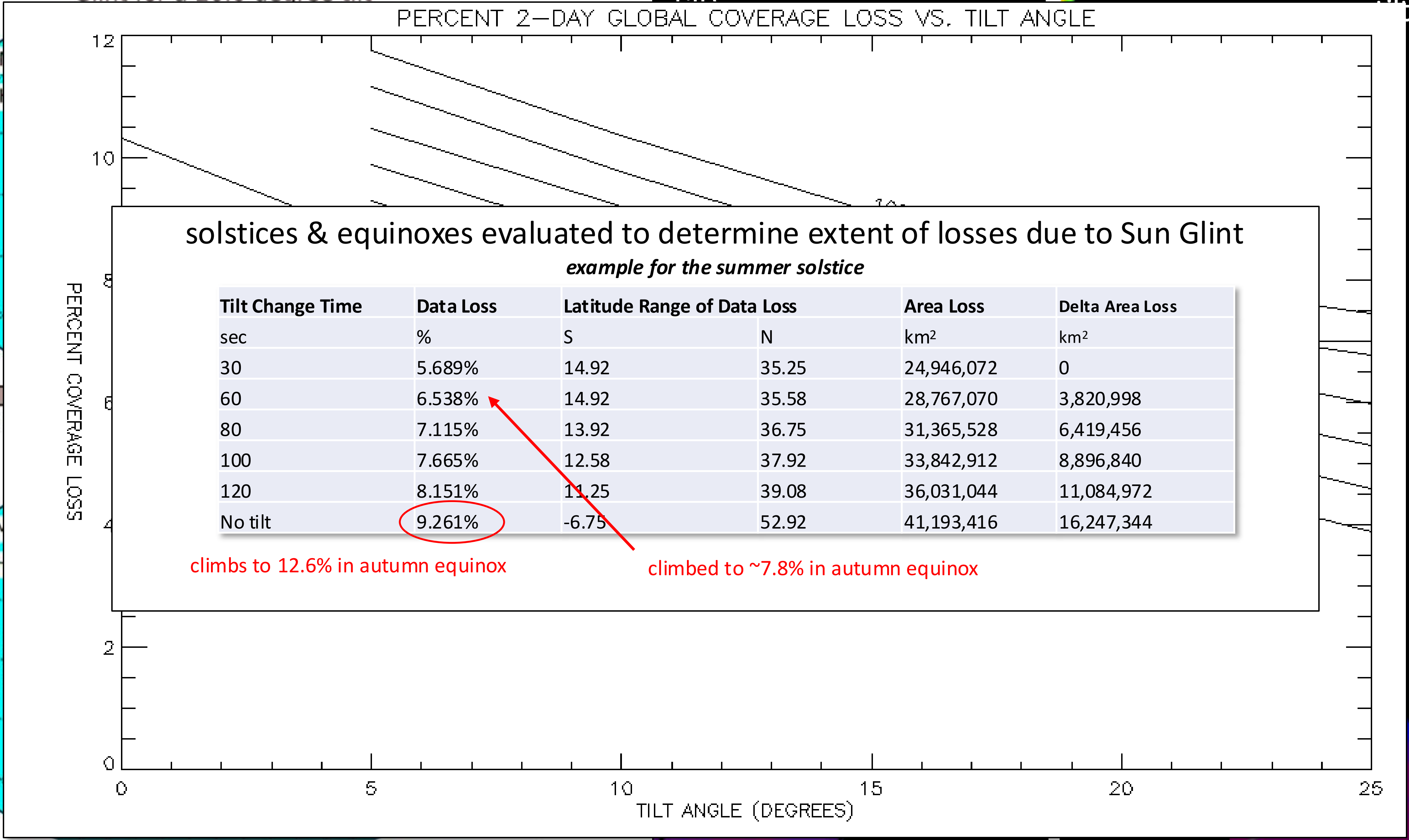


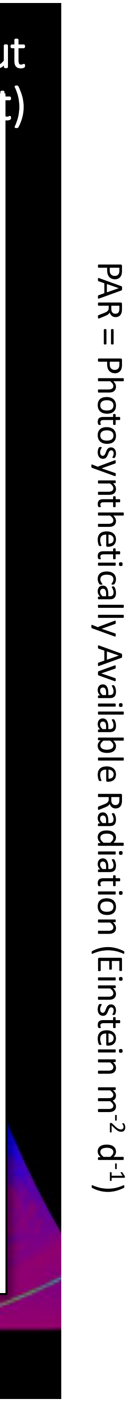
Tilt ± 20°

Spectral range goal of 320-865 @ 5 nm

Improve our understanding of how **aerosols influence ocean ecosystems & biogeochemical cycles** and how **ocean biological & photochemical processes affect the atmosphere**







solstices & equinoxes evaluated to determine extent of losses due to Sun Glint

example for the summer solstice

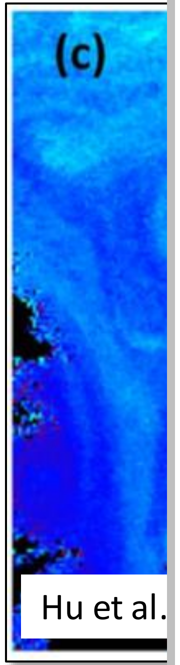
Tilt Change Time	Data Loss	Latitude Range of Data Loss		Area Loss	Delta Area Loss
sec	%	S	N	km^2	km^2
30	5.689%	14.92	35.25	24,946,072	0
60	6.538%	14.92	35.58	28,767,070	3,820,998
80	7.115%	13.92	36.75	31,365,528	6,419,456
100	7.665%	12.58	37.92	33,842,912	8,896,840
120	8.151%	11.25	39.08	36,031,044	11,084,972
No tilt	9.261%	-6.75	52.92	41,193,416	16,247,344

climbs to 12.6% in autumn equinox

climbed to ~7.8% in autumn equinox

image artifacts and instrument design

SeaWI
1



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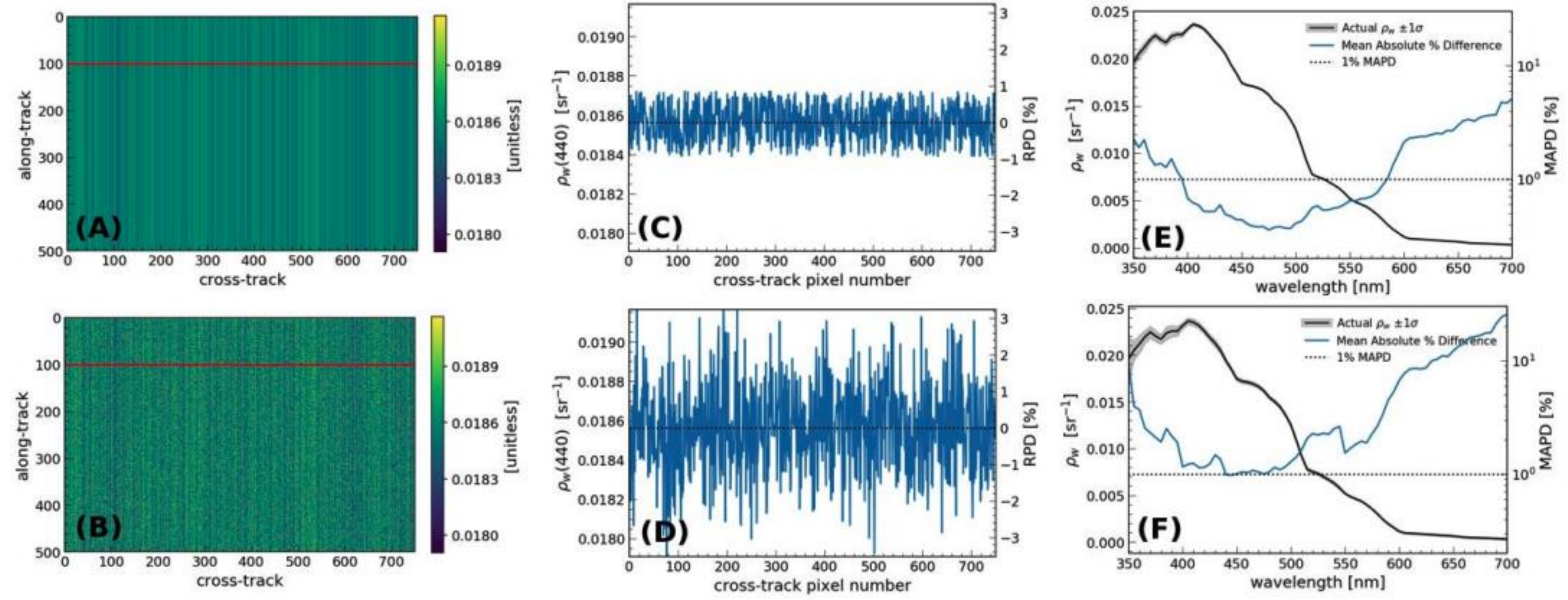
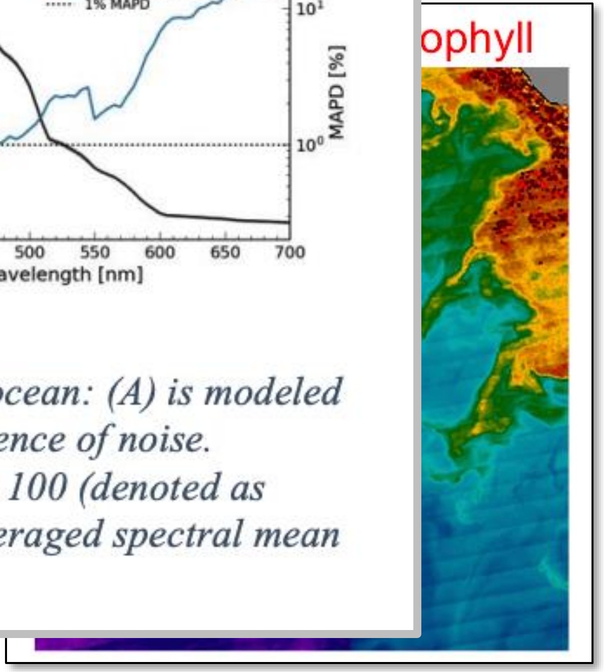
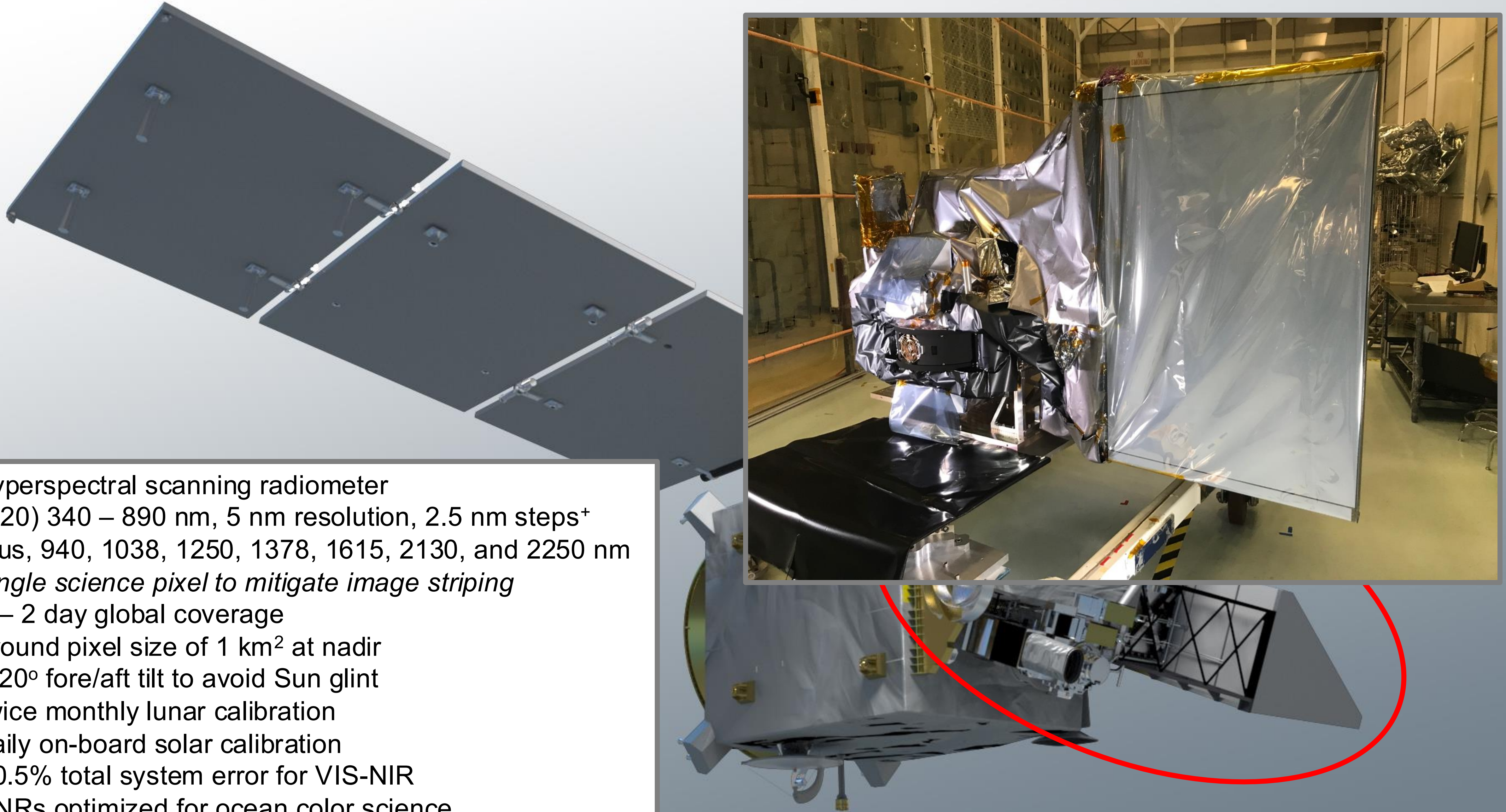


Figure 4.5: Subplots (A) and (B) show simulated pushbroom images of ρw(440) for a uniform ocean: (A) is modeled with 0.1% miscalibration error, and (B) is modeled with 0.1% miscalibration error in the presence of noise. Subplots (C) and (D) show variability in ρw(440) along a cross-track transect for scan number 100 (denoted as redlines in subplots (A) and (B)). Subplots (E) and (F) show the true ρw(λ) and the transect-averaged spectral mean absolute percent differences (MAPD).

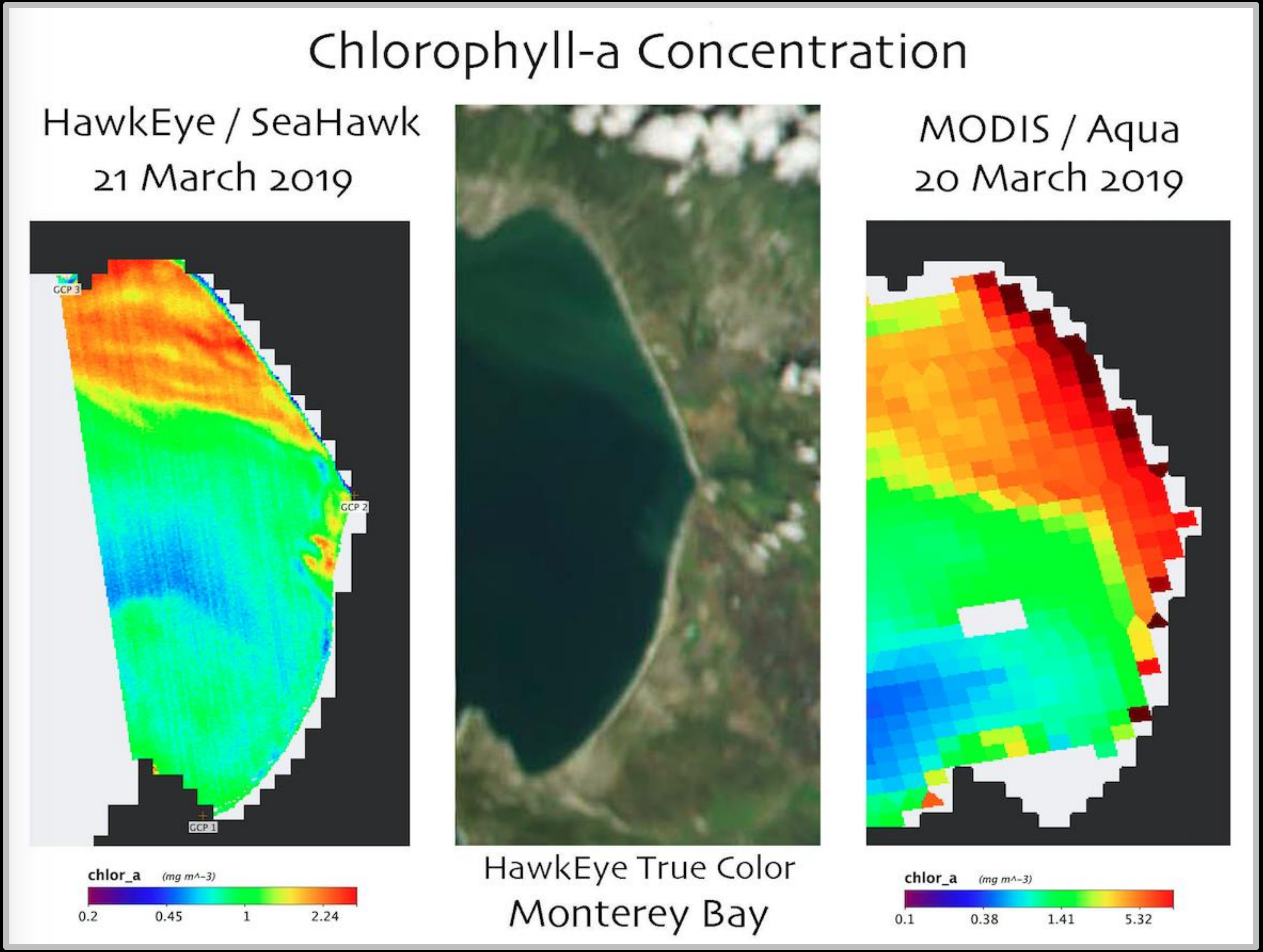




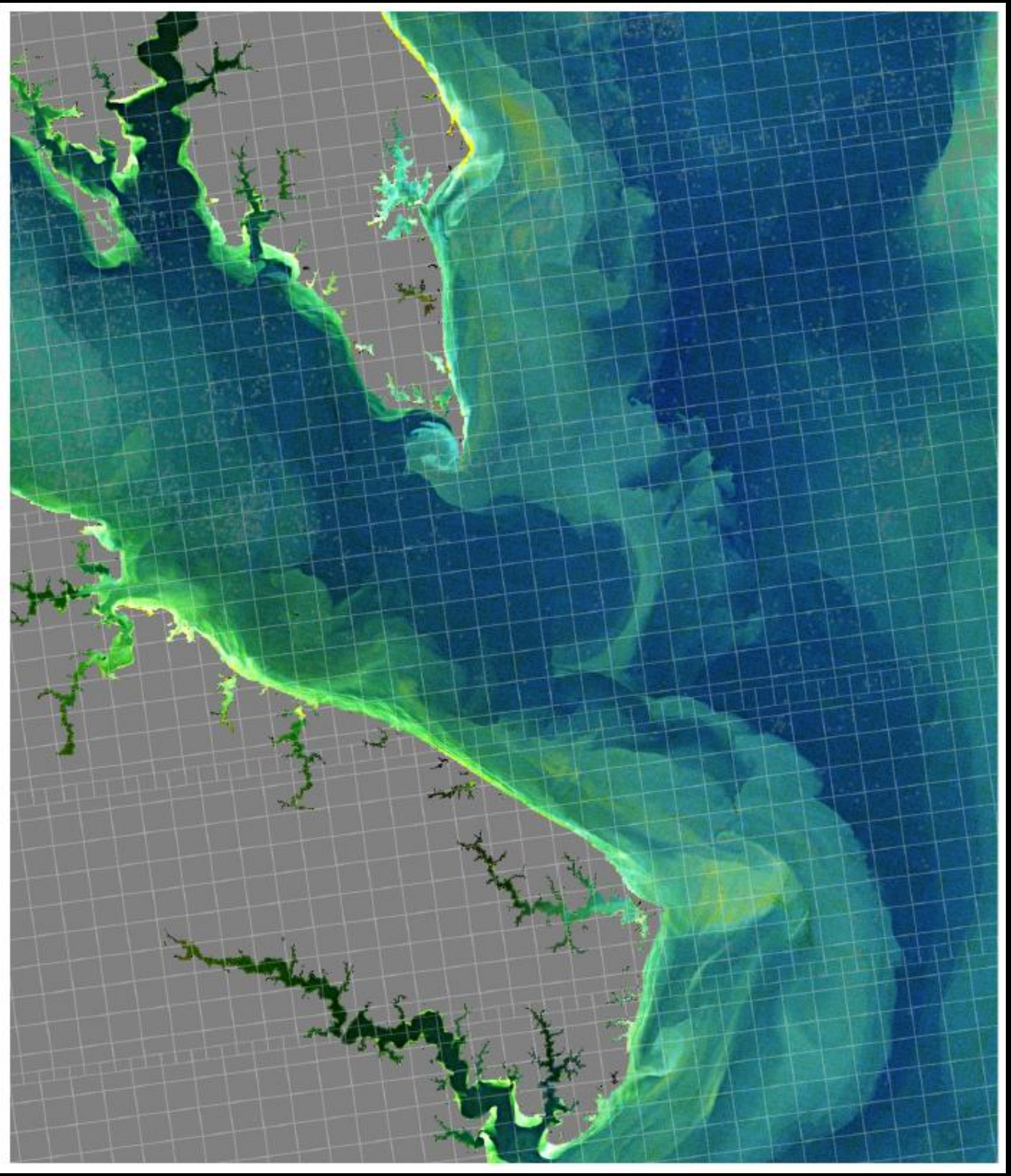
- hyperspectral scanning radiometer
- (320) 340 – 890 nm, 5 nm resolution, 2.5 nm steps+
- plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- *single science pixel to mitigate image striping*
- 1 – 2 day global coverage
- ground pixel size of 1 km^2 at nadir
- ± 20^o fore/aft tilt to avoid Sun glint
- twice monthly lunar calibration
- daily on-board solar calibration
- <0.5% total system error for VIS-NIR
- SNRs optimized for ocean color science
- simulated top-of-atmosphere data available

+ with 1.25 nm steps in several spectral regions
* developed primarily for mechanical processing assessments

all that said …



Landsat OLI image with MODIS-Aqua grid shown (Franz et al. 2015)



persevere …

persevere …

… and collaborate

#NASAESABakeoff

satellite data flows, accessibility, processing lab

to be held next week – alternating with the cruise

will include a demonstration of satellite data processing

- goal is to demystify processing from L1A to L3
- will likely include a few quick sensitivity analyses

if you want to follow along … install OCSSW between now and then

- https://seadas.gsfc.nasa.gov/
- https://seadas.gsfc.nasa.gov/requirements/
- it could (will!) present challenges – I am no help (☹), as I suffer from them too – so pretend you're at your home institution and write emails, use the forum, etc.
- but remember to have fun – it's empowering in the end!